TES FPC Flight Pulse Tube Cooler System

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ABSTRACT

The TRW Tropospheric Emission Spectrometer (TES) Focal Plane Cooler (FPC) features two integral pulse tube cryocoolers that independently control the temperature of the two instrument focal planes. The TES mission acquires high-resolution ozone concentration data in the earth's troposphere in order to better understand the ozone: where it comes from and its interaction with other chemicals in the atmosphere. TES is scheduled to fly on the EOS-Aura platform in 2002.

The TES FPC program delivered two flight coolers and electronics, and one flight spare cooler and electronics in November 1999. This paper presents data collected on the flight coolers during acceptance testing. Tests included thermal performance mapping at various reject temperatures and power levels, launch vibration testing, EMC/EMI testing, and self-induced vibration testing.

Designed conservatively for a six-year life, the coolers are required to provide 1W cooling at 57K while rejecting to 35°C with less than 63W input power to the electronics. The system (cooler and electronics) required mass is less than 17.1 kg. The system also includes radiation-hardened control electronics and provides cooler control functions with a software-controlled microprocessor.

INTRODUCTION

The TES FPC program delivered two flight cooler systems and one flight spare cooler system, plus ground support electronics (GSE) to interface with the cooler system. The program was performed for the Jet Propulsion Laboratory (JPL) over a 31-month period. The TES mechanical cooler is shown in Figures 1 and 2.

The cooler provides focal plane array (FPA) cooling via a thermal strap and rejects heat to a loop heat pipe attached to a radiator. The TES FPC system, which is the latest version of the TRW 100 series coolers, consists of the mechanical pulse tube (MPT) cooler with attached accelerometer electronics, and separately, the cooler control electronics (CCE).

The mechanical cooler is derived from the AIRS cooler which was a split pulse tube cooler. The TES cooler has been reconfigured into an integral configuration with the same cold head and the same compressor as the AIRS cooler. The electronics is the same basic design as the AIRS and MTI (currently in orbit) electronics except that the producibility was upgraded and the software was made more user friendly.

Before installation and operation of the cooler on the instrument, both the mechanical and the electronics assemblies together with the operating software underwent flight level acceptance testing, including environmental tests of launch vibration, thermal vacuum cycling, EMI/EMC testing,

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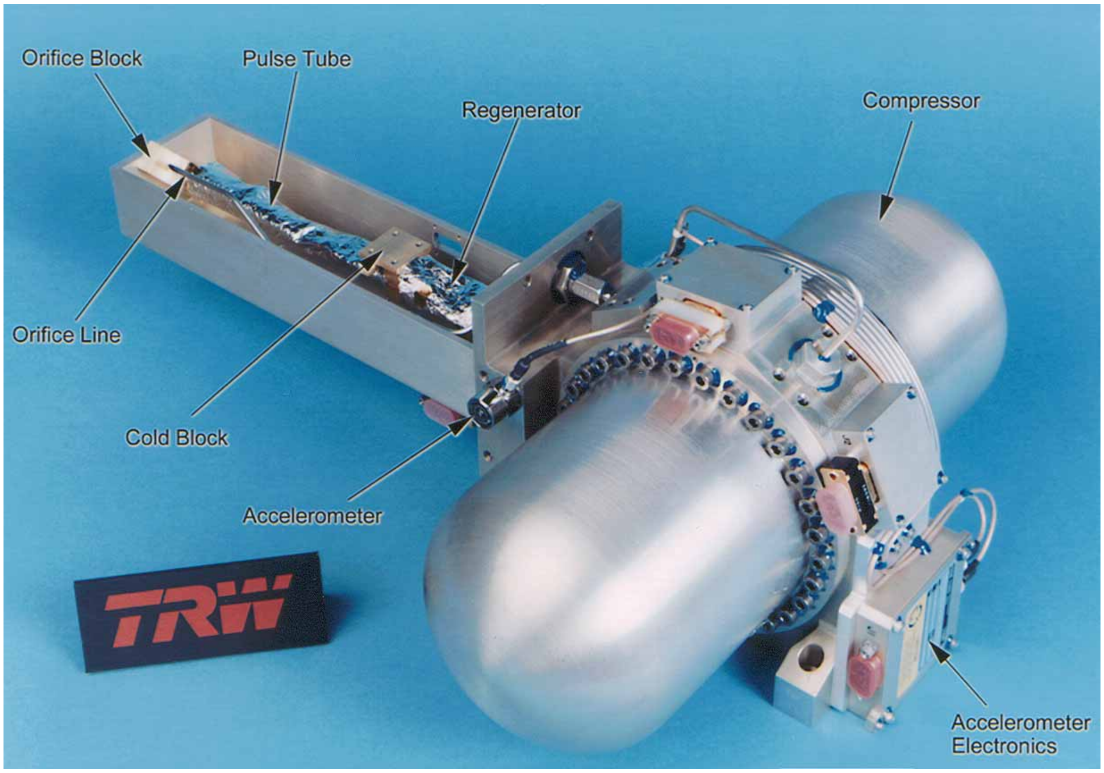

Figure 1. Integral vibrationally-balanced pulse tube cooler.

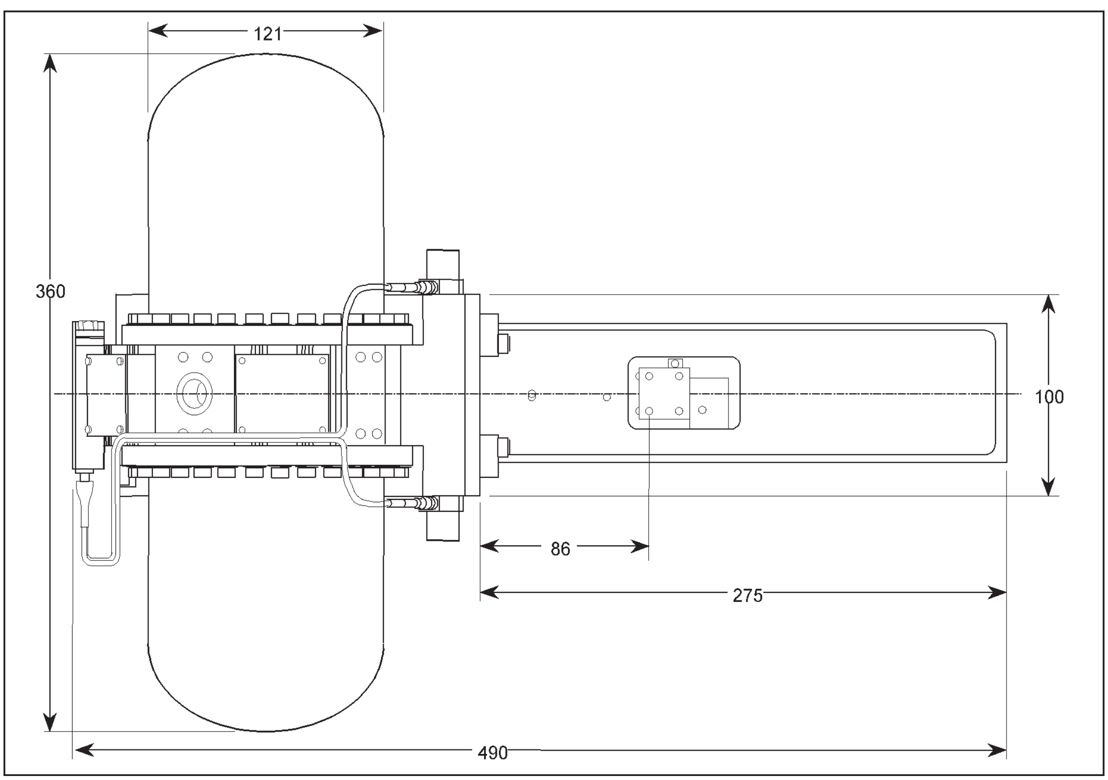

Figure 2. TES FPC envelop for the mechanical cooler.

and burn-in. These tests, which are typical for space instruments, are performed to ensure reliability. The cooler performance, including load lines, temperature stability, self-induced vibrational force, and EMI/EMC properties, was measured. This paper reports the test data for one of the new flight coolers. There was less than 6% input power difference from unit to unit at the nominal operating condition of 1W at 57 K.

COOLER SYSTEM

The mechanical cooler (Figure 1) refrigerates via the cold block, rejecting heat at the centerplate of the compressor. Inside the compressor, flexure springs support the moving-coil linear motor, which drives the pistons. The springs maintain alignment for the attached non-contacting piston that oscillates and compresses gas into the pulse tube cold head. A small clearance between the cylinder and the piston seals the compression space. Two opposed compressor halves vibrationally balance the compressor. The compressor is operated at the resonant frequency of 44.6 Hz.

Capacitive sensors are used to measure the position of both pistons. The output is used to measure and control dc offset and to provide overstroke protection. The pulse tube cold head is bolted to the compressor centerplate, and is sealed with a metal seal. The centerplate conducts heat to the radiator and incorporates the reservoir tank. The cold head components are arranged linearly: mounting flange, regenerator, cold block, pulse tube, and warm-end heat exchanger body (or orifice block). The cold head is surrounded by an H-bar that supports and provides a thermal path to remove heat from the orifice block. The stainless steel orifice line and bypass line connect the gas from the orifice block to the reservoir tank and to the aftercooler, respectively.

The internal wiring in the compressor is stranded, PTFE-insulated (cross-linked Teflon) wiring, or Kapton flexible cable. All wiring exits the centerplate through ceramic-insulated pins in feedthroughs attached to D-shell connectors for the cooler drive power and to the capacitive sensors and thermistor. A separate connector is used for the redundant platinum resistance thermometers (PRTs) on the cold block. Redundant accelerometers are mounted on the compressor centerplate. Together with the signal conditioning electronics, the accelerometer provides a feedback signal to the vibration control algorithm in the cooler control electronics (CCE).

The CCE (Figure 3) is based on our high-reliability AIRS flight design[1] modified for producibility. New features include the horizontal slice design as shown in Figure 3 and additional internal connectors to allow for slice-level testing. There are three slice subassemblies, one for control (control slice), one for power amplifiers (power slice), and one for power conversion (converter slice) . The

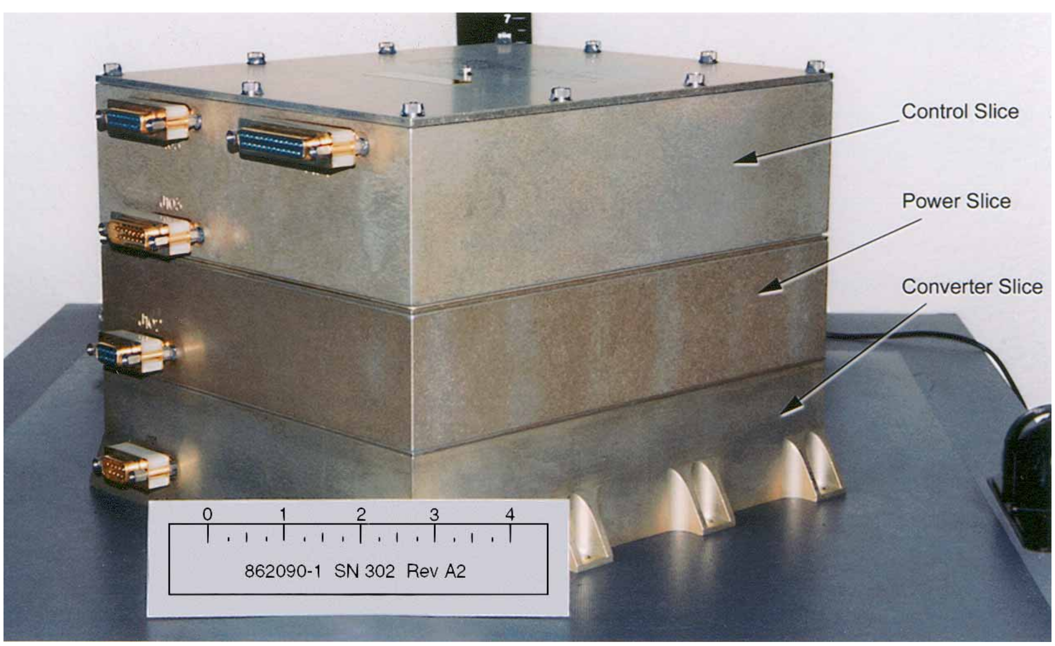

Figure 3. Cooler Control electronics (CCE).

Table 1. Cooler System Capabilities vs. Instrument Requirements

Instrument	Requirements	Capabilities
Cooler Mass Electronics Mass	10.6 kg 6.3 kg	10.6 kg 6.3 kg
Nominal Operating Condition Cooling Load Cooling Temperature Heat Reject Temperature Bus Power	 1.0W 57K 308K <63W	 1.0W 57K 308K 58.7W
Maximum Cooling Load Cooling Temperature Heat Reject Temp Bus Power		2.7W 57K 308K 151W *
Temperature Stability	0.1Kp-p reject 0.2°C/min	0.022Kp-p reject 0.21°C/min
Operating Temperature Range (TMU)	-15 to 50°C	-15 to 50°C
Non-operating Temperature Range (TMU)	-20 to 65°C	-20 to 65°C
Operating Temperature Range (CCE)	-20 to 60°C	-20 to 60°C
Non-operating Temperature Range (CCE)	-30 to 65°C	-30 to 65°C
Launch Vibration (TMU)	7.2 Grms, 1 min	7.2 Grms, 1 min
Launch Vibration (CCE)	9.1 Grms, 1 min	12.1 Grms, 1 min
Bus Voltage Range	27V to 31V	21V to 35V
Inrush Current	< 10 amp	4.2 amps
Ripple Current	< 127 dB micro amps	123 dB micro amps
Communication Protocol	RS422	RS422
Lifetime	>5 years	10 years

* Based on power output limit of 120W on CCE

slices are housed in a standard subassembly that is 225 mm (L) x 216 mm (W) x 175 mm (H). The bottom of the housing serves as a mounting surface for direct thermal contact. The electronics in the CCE: (1) converts the 28 Vdc primary power to the secondary power, (2) drives the cooler, and (3) provides communication with the host and control of the cooler with a processor using software resident in PROM. The software performs the following functions:

- Transmits spacecraft command and cooler telemetry via the RS422 data bus
- Collects the cooler state of health data
- Controls the cold block temperature
- Actively balances vibration force by controlling the waveform of the pistons
- Provides safety protection to the cooler

COOLER OPERATION AND CAPABILITIES

Table 1 summarizes system weight and capabilities. The cooler electronics provide AC drive power at 44.6 Hz to the motors in the compressor. The compressor moving coil and piston assemblies are designed to resonate on their gas and mechanical springs at this drive frequency, and thus generate a 44.6 Hz pressure wave and mass flow to the cold head. The software adjusts the stroke to maintain the desired cold block temperature. The vibration control algorithm samples the accelerometer signal and determines, by Fourier analysis, transfer gains and error signals for up to 16 harmonic frequencies. The error signal modifies the motor drive waveform to reduce vibration.

Figures 4 and 5 show the cooling load as a function of cooling temperature for different reject temperatures and input powers. For the TES FPC nominal cooling load of 1.0 W at 57 K, the cooler system requires 58.7 W of input power and the compressor operates at 45.5% stroke. For a TES FPC cooling load of 0.5 W at 57 K, the cooler system requires 34.5 W of input power and the compressor operates at 35.8% stroke.

The CCE (Figure 3) plays a critical role in the overall cooler performance. When the input bus power (P_B) was measured as a function of the output power to the compressor (P_c), it fit the straight-line correlation:

$$P_B = P_c/\eta + P_t \qquad (1)$$

where the efficiency (η) is 0.825, and the extrapolated tare power at zero compressor power is P_t = 5.5 W.

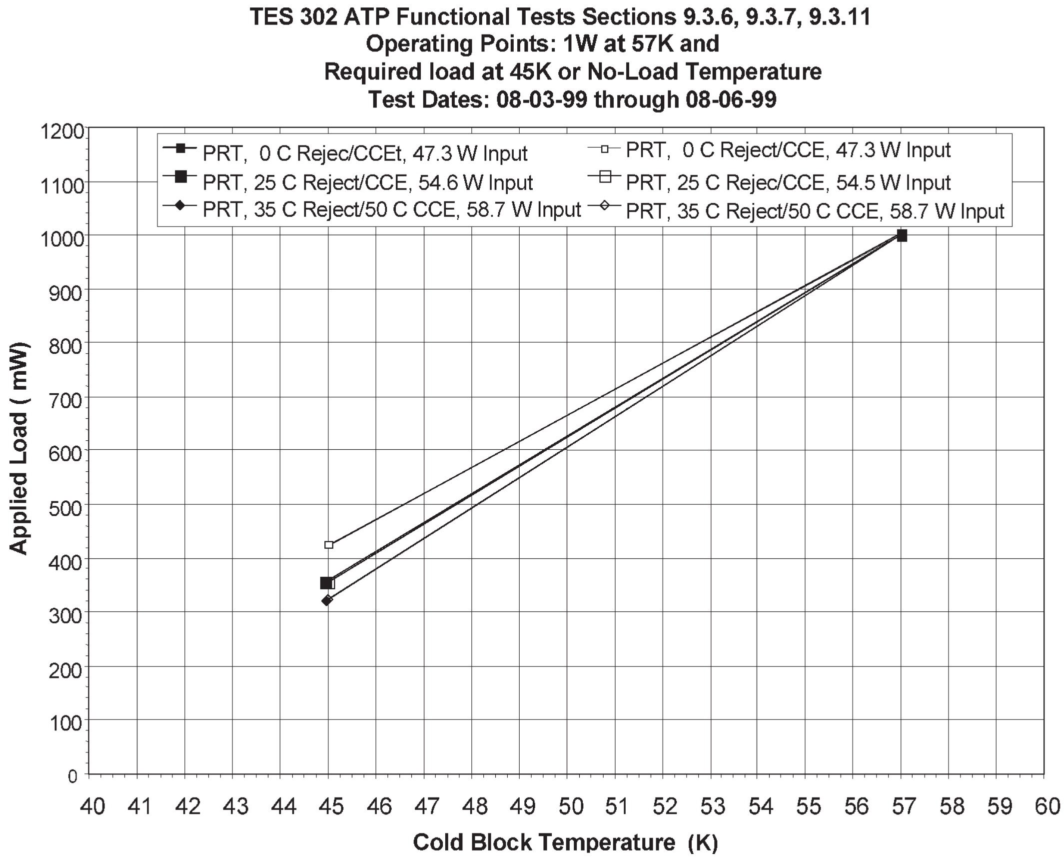

Figure 4. Cryocooler performance for variable reject temperatures: 1W at 57K.

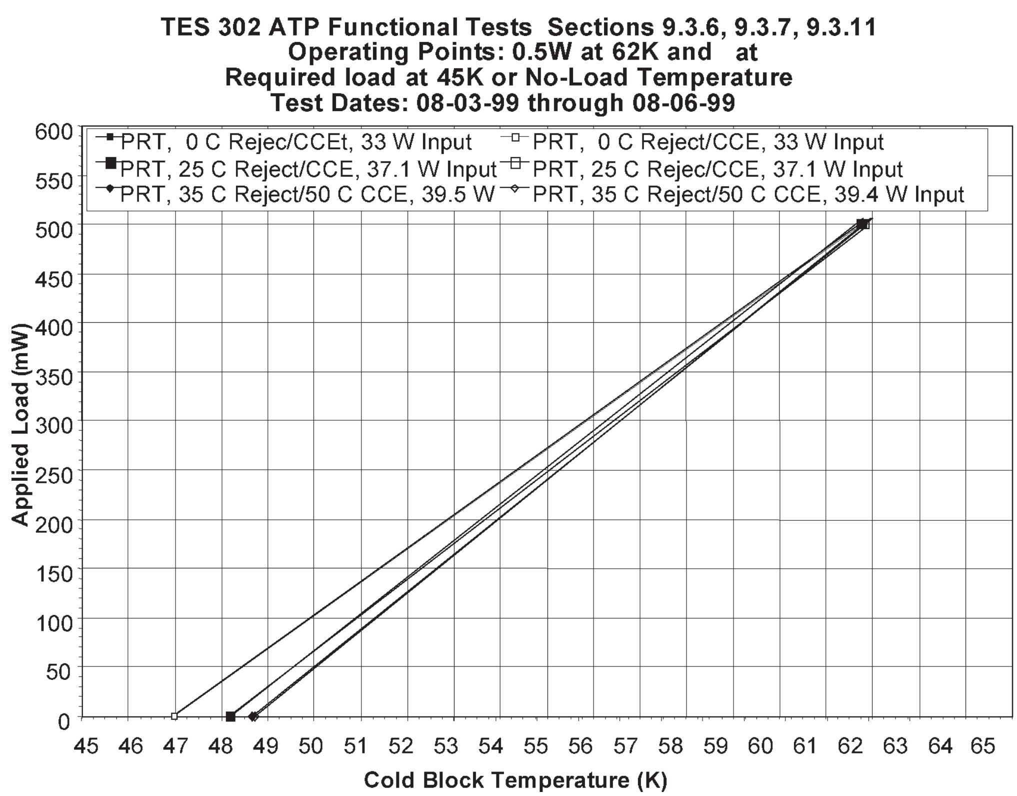

Figure 5. Cryocooler performance for variable reject temperatures: 0.5W at 62K

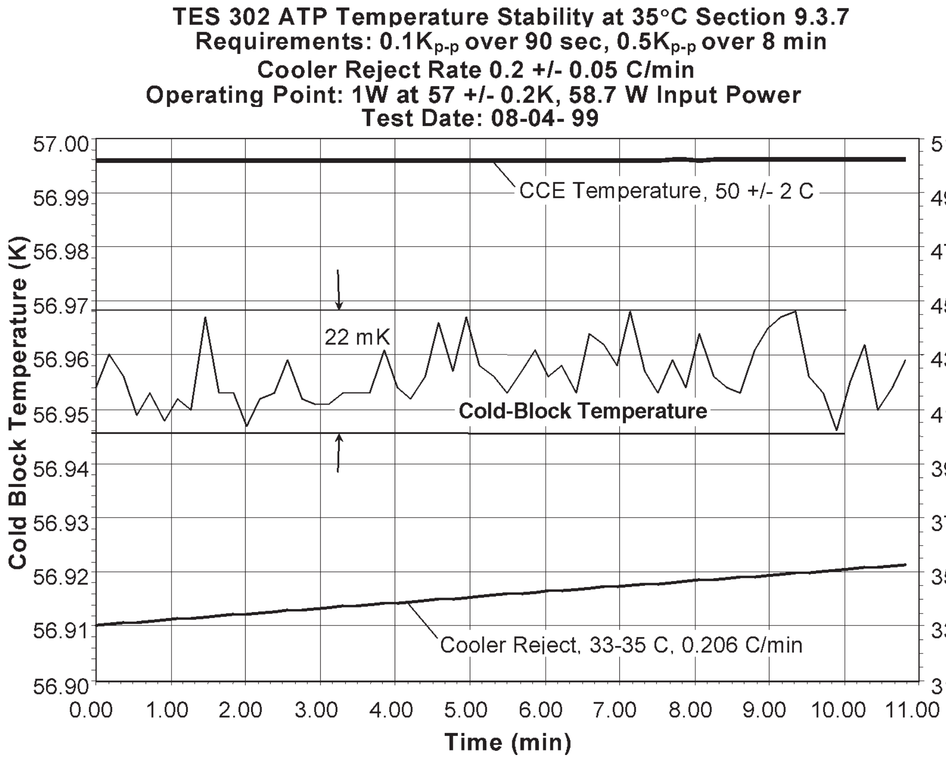

Figure 6. Temperature stability maintained by control loop during simulated orbital temperature change.

The temperature control algorithm adjusts the stroke level based on the difference between the cold block PRT temperature and the set point temperature value. Figure 6 shows that the temperature stability of the cooler is within a 22 mK band when operating with a 1-W load at 57 K and a baseplate temperature change of 0.21°C/min. The resolution of one bit in the temperature measurement electronics is 12 mK.

The vibration control algorithm continuously updates the compressor waveform to minimize cooler vibration. TRW's special purpose dynamometer measures the three axes of the self-induced vibration of the cooler. Figure 7 shows the force in the direction of piston motion (cooler axis) as well as the two cross axes when the cooler is mounted on a rigid structure.

ENVIRONMENTAL TESTS AND COOLER ACCEPTANCE

The TES FPC acceptance testing included launch random vibration, a thermal vacuum test with operating and non-operating temperature cycles, and burn-in. Levels and ranges for these tests are summarized in Table 1. Repeatable cooler performance after each environmental test is used as an acceptance criterion. The cooler was accepted because no performance change of the load line was detected within experimental uncertainty. The measured helium leak rate was two orders of magnitude less than the 5-year-life criterion and satisfied a 10-year-life requirement.

EMI/EMC TEST

The cooler system must meet stringent requirements for radiated electric and magnetic fields, conducted emissions on the input bus power lines, and electromagnetic susceptibility. Excessive magnetic fields are a generic issue with linear-motor cryocoolers, as are excessive levels of input ripple current. The TES FPC is an integral version of the TRW AIRS design, which required magnetic shielding to pass the radiated magnetic emission requirement.[2] The TES FPC will be fitted with this shield design. TRW's newer cooler designs meet the radiated magnetic emission requirements without the need for shielding.[3]

The in-rush currents and the ripple currents for the nominal 29 V bus voltage requirement were

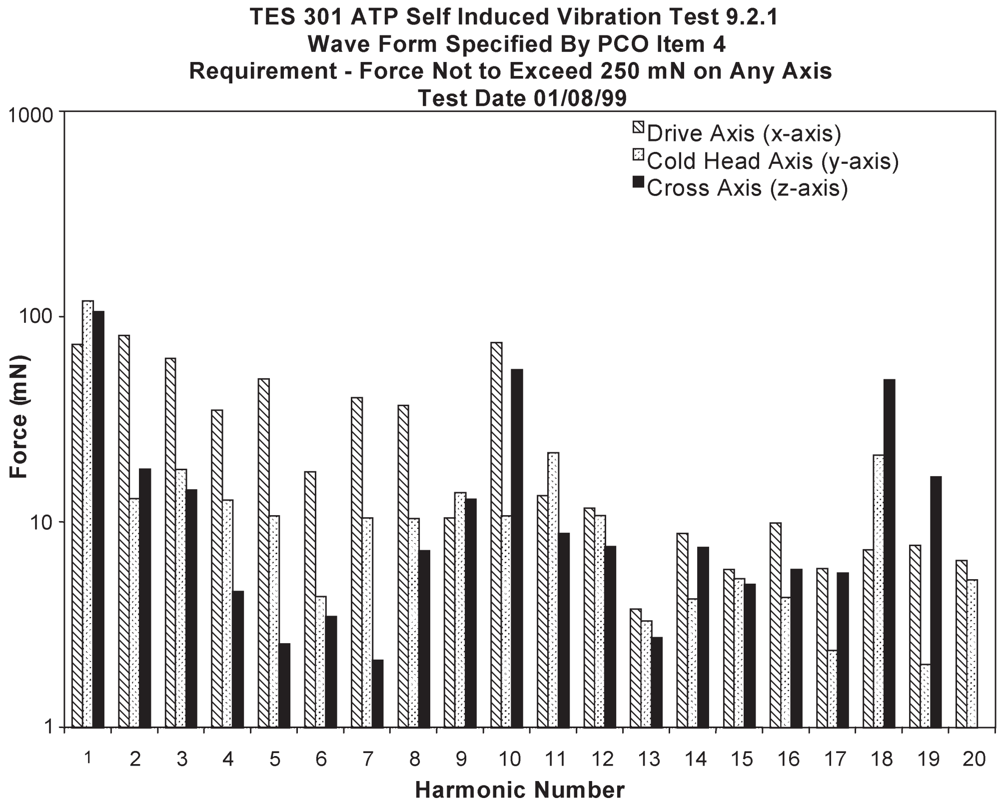

Figure 7. Measured self-induced force of compressor in three axes at 46 compressor stroke level and 42.6W into compressor.

recorded as 4.2 amps and 123 dB micro amps, respectively (Table 1). TRW's latest electronics have modified the TES FPC design to considerably lower the ripple current.[4]

The EMI and compatibility EMC qualification tests were performed at the TRW EMI test facilities to determine the degree of compliance to Mil-Std 461C requirements, as modified in TRW BDA-14A-001, EMC Test Procedure for the TES FPC program. Table 2 summarizes the test matrix. During the test series, two tests failed to meet the requirement. For the conducted emissions (CE03), an overlimit condition was observed at 200 and 100 kHz in the narrowband mode (Table 2). An external filter at the input of the CCE will enable the cooler system to meet CE03.

Table 2. EMI Test Matrix

TES FPC	
Test Description	**Meet/Not Meet Requirements**
Conducted Emissions (CE)	
CE01 – 30 Hz to 20 kHz NB, BB	M
CE03 – 15 kHz to 50 MHz NB, BB	N**
Radiated Emissions (RE)	
RE02 - 14kHz to-18 GHz	M
Conducted Susceptibility (CS)	
CS01 – 30 Hz to 20 kHz	M
CS02 – 20 kHz to 400 MHz	M
CS06 – Transient Spike	M
Radiated Susceptibility (RS)	
RS01 – 30 Hz to 200 kHz	M
RS03 – 14 kHz to 18 GHz	M

**The out of specification values are as follows.

@ 100 kHz: 8 dBuA/MHz over limit (29V & RTN)

@ 200 kHz: 21 dBuA/MHz over limit (29V & RTN)

CONCLUSIONS

The TES FPC performance met the program goals. The coolers were delivered in October 1999 and are awaiting integration with the payload.

ACKNOWLEDGMENT

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